Ground Effect due to Periodic Resonant Roughness

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Summary
Traffic noise is an ever-increasing problem due to the gradual urbanisation and growing popularity of motorised means of travel. Land between roads and nearby noise-sensitive receivers can be used to support a series of low-rise roughness structures as an alternative to conventional earth berms and noise barriers. Through measurements in an anechoic chamber and numerical computations using a two-dimensional boundary element method, we have investigated the effect of periodic roughness elements above a smooth hard surface on sound propagation. First, an array of solid rectangular roughness structures was studied to investigate the effect of the periodicity-induced diffraction. The broad-band insertion loss with reference to smooth hard surface was found to be considerable for near-grazing incidence. However, at frequencies below the first roughness-induced destructive interference, negative insertion loss was also observed due to the creation of surface waves by the roughness elements. To improve the insertion loss in this low-frequency range, we have investigated the use of hollow resonant elements with slit openings constructed from pairs of aluminium angles, and observed the desired effect while maintaining the insertion loss at higher frequencies. Also we have created double-resonant roughness elements by inserting pairs of smaller aluminium angles within the larger structures and have measured associated multiple resonances.

PACS no. 43.20.Fn, 43.20.Ks

1. Introduction

Traffic noise has been a constant source of a nuisance since the invention of the wheels even in the ancient times. This has been further aggravated in the modern days due to the introduction of the motorised means of travel and the urbanisation of the population. This has already reached a point where the traffic noise, in conjunction with other types of acoustic noise, can affect the daily lives and well-being of the people.

Several mitigation methods have been devised and implemented. The latest motor vehicles have more streamlined shapes than their predecessors and are fitted with quieter engines and exhaust systems which could be further improved by the advent of hybrid or electric vehicles. Much research has been carried out on the interaction of the tyres and the road surface. Bypass road networks have also been built, effectively reducing the level of noise exposure to dwellers. Regulations have been put in place, for example, to impose speed limits, although the noise reduction may not be the primary reason for doing so.

The most common 'passive' means of traffic noise abatement is the erection of a high-rise noise barrier alongside a busy road. This has been ubiquitous, when not much free land is available, for noise reduction and hence to enhance the quality of the daily lives for the nearby residents. However, the barrier has been often considered as an eye sore due to its negative aesthetic impact on the road users and residents; sometimes, local people oppose the introduction of a barrier. As a potential remedy, modification such as transparent barriers have been constructed. A barrier with partial opening such as sonic crystals has been researched recently, which has a potential due to tunable frequency range and reduced wind loading. Combination of both conventional noise barrier and sonic crystal has been recently reported also [1].

When sufficient land is present, high-volume and high-rise earth berms have also been built especially alongside high-speed motorways. Leftover soils can be recycled from a nearby construction site. Vegetation belts of 15 m width and various planting schemes were also numerically studied, and it was suggested that the acoustic performance of such vegetation belt could be comparable to a 1.5-m high thin noise barrier [2].

In this paper, as an alternative solution to the high-rise structure of conventional noise mitigation, we explore the feasibility of noise reduction by a low-rise roughness structure on the ground. This approach can be applicable as long as sufficient land is available between the road and the nearby dwellings and can be an interesting alternative to earth berms. Instead of constructing a large structure of earth mounds, displaced soil can be used to build a series of low-rise roughness elements. This can be aesthetically more pleasing and reduce the cost of construction and maintenance compared with earth berms.

In the following section, we present laboratory studies of the ground effect on the sound propagation due to periodic and resonant roughness structures. Experiments have been carried out at the anechoic chamber at the Open University. These have been compared with the numerical results obtained by the two-dimensional boundary element method (BEM).

2. Methods

We have built small-scale roughness structure on an acoustically-hard board inside an anechoic chamber. An acoustic source and a microphone were placed close to the surface to investigate the near-grazing incidence.

The measurement was performed in two steps. First, the response of the bare board was measured. Then, the response of the board with roughness elements was measured. During the measurements, the position of the acoustic source and the microphone was fixed.

We then calculated the insertion loss (IL) of the roughness elements referenced to a smooth hard surface by calculating the transfer function between the responses of each measurement pair. The numerical insertion loss corresponding to the configuration of each measurement was also calculated through BEM.

3. Materials

Two metre long aluminium angles with two different sizes were assembled to construct roughness elements. The detailed dimensions are shown in Figure 1.

For a smooth surface, we used a 10-mm thick plastic board with the dimension of 122 cm $\times$ 138 cm. To accommodate the 2-m long angles, the sides of the plastic board were extended by 5-mm thick glass sheets. Care was taken to ensure the smooth transition between the plastic board and the glass sheets.

4. Non-resonant periodic roughness structure

The acoustical effects of a series of small-scale roughness structures periodically placed on a smooth hard surface have already been studied [3]. We present, first, the BEM calculation of the non-resonant periodic roughness structure on a smooth, acoustically hard surface. The simulated IL spectra predicted for 6 and 20 roughness elements are compared in Figure 2. The heights of the source and receiver are 81 and 60 mm respectively. The horizontal range for the source to the receiver is 90 cm and 3 m respectively for 6 and 20 elements. The centre-to-centre spacing is 15 cm and the elements are positioned periodically. The measurement of the six elements were also carried out, but is not presented here in detail due to a strict page limit. We can report that the measurement and BEM simulation was in a good agreement.

Although the line-of-sight between the source and the receiver was secured for this configuration of near grazing incidence, the insertion loss we can achieve is demonstrated to be considerable depending on the frequency range of interest. However, it is noted that the benefit will be reduced for higher source and receiver positions. It is clear that for the most of the calculated frequencies the predicted insertion loss is higher if there are more roughness elements. However, there is one exception. For frequencies below 1 kHz, one can see that the performance of 20 elements was worse than that of the lesser 6 elements.

This negative insertion loss below 1 kHz is evidence that a surface wave is generated by the periodic roughness structure. It is also widely known that it takes some distance for a surface wave to develop. That is why we did not witness the surface wave for the 6 roughness elements.

In the context of traffic noise mitigation, Figure 2 demonstrates that a higher insertion loss can be achieved when more land is available between the road and the nearby residential or industrial area. However, when a very low frequency is of particular interest, this can be equally disadvantageous as the surface wave develops. This can be helped by the A-weighted nature of human hearing to some extent. But we do not apply the weighting in this work due to the nature of scale-model investigation. In general, to address the low-frequency noise, we need bigger structures. However, this obvious solution is not necessarily viable. Therefore, it would be ideal if we can filter out some of the surface wave while maintaining the positive insertion loss at higher frequencies without resorting to scaling up the structure.

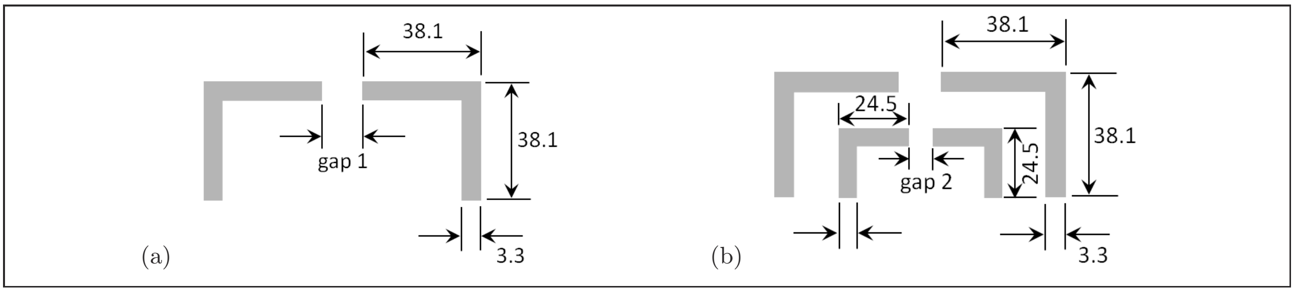

Figure 1. Cross-sectional dimensions of aluminium angle structure. (a) a single structure. (b) a double structure. The dimensions are in mm. For the data presented in this work, gap1 is fixed at 6 mm.

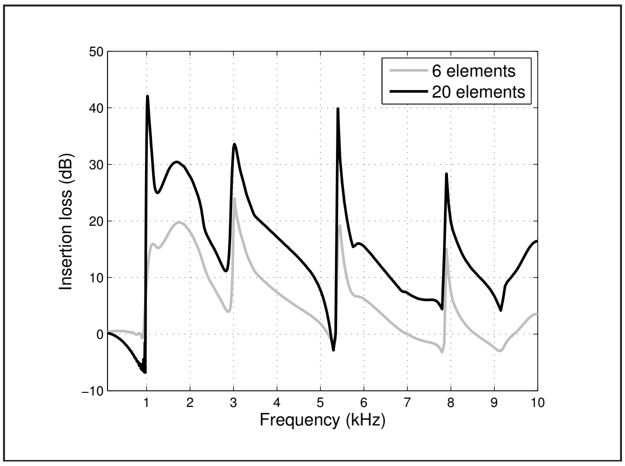

Figure 2. The comparison of the predicted insertion loss for 6 roughness elements (in grey) and 20 elements (in black) periodically placed on an acoustically-hard surface. Both elements are non-resonant of the same size. Heights of the source and receiver are the same, but the range is different.

5. Single-resonant periodic roughness structure

Resonators have been implemented in many applications to reduce the sound at particular frequencies: Helmholtz resonators in concert halls, for example. As an extension to a conventional sonic crystal, Krynkin et al. [4] demonstrated that the insertion loss was markedly changed around the resonant frequencies inherent to an array of hollow cylinders with slit openings We apply this mechanism of resonance to roughness elements placed on the base surface. Krynkin et al. [4] restricted their investigation to 'circular' cylinders due to the ease in handling them theoretically in the cylindrical polar coordinate system. To keep the circular shape and required dimension, they could not carve the slit all along the length of the cylinder: the slit was discontinuous in every 20 cm or so. In contrast, the angles shown in Figure 1 can keep the slit continuously along the entire length and can be easily modelled by BEM.

For the components shown in Figure 1(a), we have kept exactly the same geometry and configuration as those of the non-resonant roughness elements in the preceding section. Figure 3 shows the BEM comparison between the resonant elements in Figure 1(a) and the solid rectangles whose insertion loss was already shown in Figure 2: both elements have the same outer dimension. One can see the considerable change in IL at the frequencies where the surface wave is likely to occur should the number of elements be sufficient to generate a surface wave. Just short of 1 kHz, the predicted IL value is dramatically increased. However, it is also noted that below those beneficial frequencies the situation gets worse. This phenomenon assoicated with resonant elements made of hollow structure with slit opening was also demonstrated by Krynkin et al. [4]. In both Krynkin et al. [4] and here in Figure 3, we observe more advantage than disadvantage.

At frequencies higher than 1 kHz in Figure 3, one can notice that the overall level of beneficial insertion loss is at least retained for the resonant structure with often increase in the frequencies likely corresponding to the higher modes of the resonance. Therefore, it is clear that the introduction of the resonant mechanism to the roughness elements is largely beneficial.

We have also conducted the measurement corresponding to this resonant configuration. Six of these resonant structure were placed on the extended board. The near side of the first element was placed 5 cm horizontally from the exit of the acoustic source. Then, they were arranged axially parallel to one another. The centre-to-centre spacing was chosen to be 15 cm. The tip of the microphone was secured horizontally 90 cm away from the source. The measured heights of the source and the receiver were 81 and 60 mm respectively. Both source and microphone were positioned horizontally that is parallel to the surface of the board. An imaginary line connecting the loudspeaker and the microphone was perpendicular to the axes of 6 roughness components, which makes it possible to interpret the measured data as if they were obtained two-dimensionally despite the fact that the actual measurement was carried out using a point source.

Figure 4 shows both the measured and predicted insertion loss for this resonant arrangement. We are satisfied by the good agreement over the whole fre-

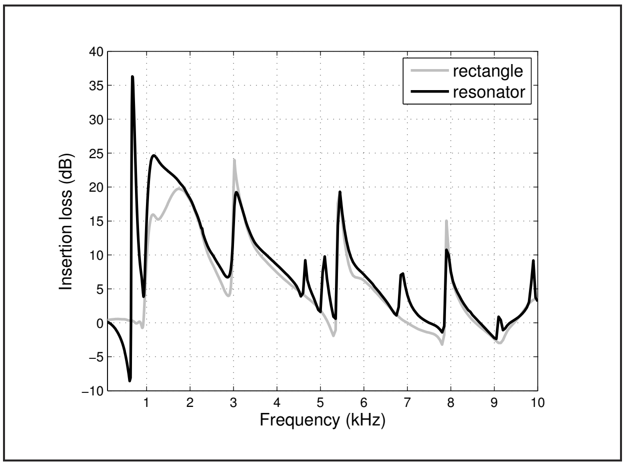

Figure 3. The comparison of the predicted insertion loss for 6 non-resonant rectangular roughness elements (in grey) and 6 resonant elements (in black) periodically placed on an acoustically-hard surface.

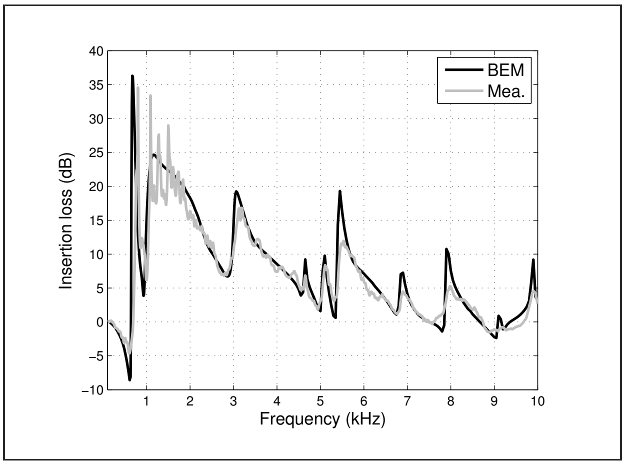

Figure 4. The comparison of the insertion loss measured (in grey) and predicted by BEM (in black) for 6 resonant roughness elements periodically placed on an acoustically-hard surface.

quency range of measurement. It is encouraging to see even the minor discrepancies from the non-resonant spectrum shown in Figure 3 are well portrayed in the measured data.

6. Double-resonant periodic roughness structure

Although it was demonstrated that the impact of the resonance could be mostly positive, it was also shown that the performance can get worse for a very low frequency. Therefore, it would be ideal if there is a way to improve or change the IL at frequencies where it is made worse. Should it be desirable to keep the response of the overall frequencies and a necessity arise to alter the spectrum at particular frequencies, the introduction of additional resonances at different frequencies may be considered.

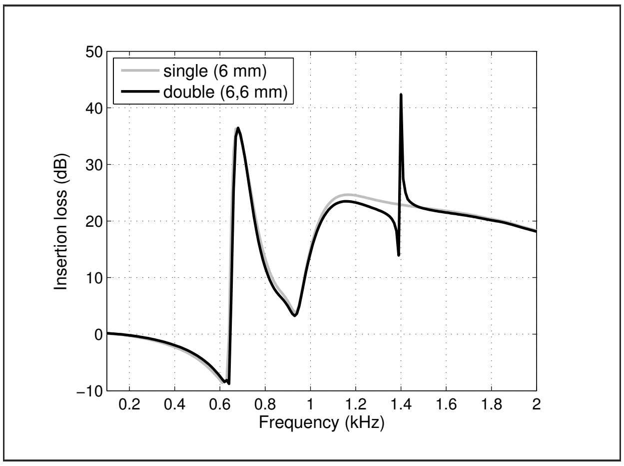

Figure 6. The comparison of the predicted insertion loss for 6 single-resonant roughness elements (in grey) and double-resonant elements (in black) periodically placed on an acoustically-hard surface. Both single and double structures have the gap of 6 mm for all slits.

Elford et al. [5] proposed a modification to a conventional sonic crystal by adopting a concentrically repeated arrangement of circular hollow cylinders with slit openings, a resemblance to the nested arrangement within a Russian doll. They numerically studied, by using the finite element method (FEM), an array of sonic crystal elements each of which was composed with up to 6 or 7 nested circular shells. No measurement was reported in their work. It was concluded that their design could produce multiple resonance band gaps which could be potentially beneficial in an application to road traffic noise reduction.

In this paper, we apply the same strategy of placing a smaller resonant structure within a larger one. To demonstrate the feasibility of this idea we have investigated a double structure only. It is also noted that our proposal of using L-shaped angles is easier to implement and hence validate by the corresponding measurement than the circular counterpart.

We tested the configuration shown in Figure 1(b) for a double resonant roughness elements. All the dimension of the outer element including the slit gap are the same as those of a single resonant structure in Figure 1(a). Figure 5 shows the numerical comparison of the insertion loss between single and double-resonant elements on the smooth surface. The ‘gap2’ (indicated in Figure 1(b)) at the inner structure is 1 mm. It is observed that in higher frequencies the overall spectra are similar each other with only occasional changes. However, the shifting of the first resonance and the introduction of the second resonance are certainly of interest in case even a lower frequency needs to be addressed.

Figure 6 demonstrate how the width of the inner slit affects the IL performance in double-resonant structure. Only the case of 6 mm is shown for brevity. In comparison with Figure 5(b), it is shown that

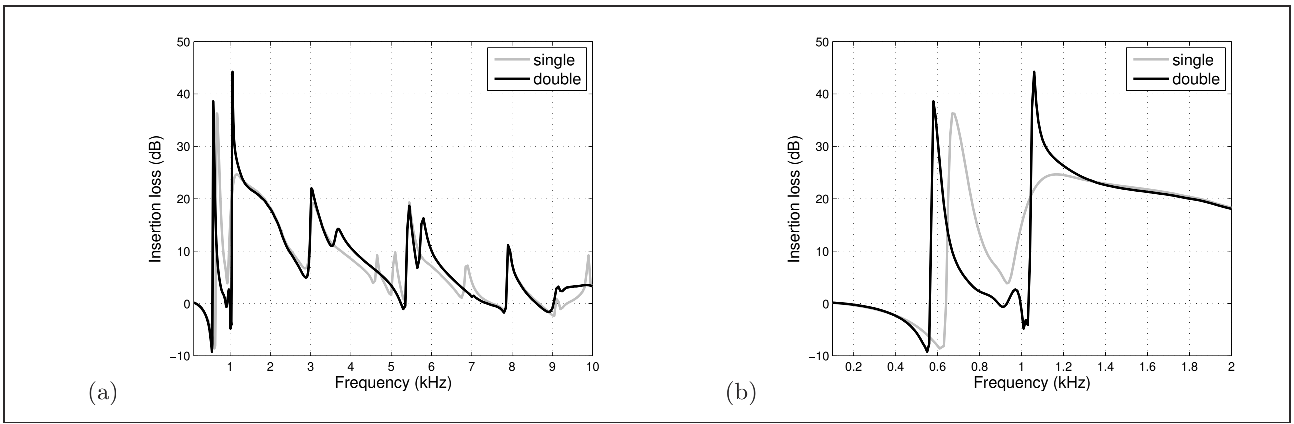

Figure 5. The comparison of the predicted insertion loss for 6 single-resonant roughness elements (in grey) and double-resonant elements (in black) periodically placed on an acoustically-hard surface. The inner slit gap is 1 mm for the double structure. (a) frequency range up to 10 kHz. (b) frequency range up to 2 kHz.

the wider the inner gap, the higher the resonant frequencies. This implies that, with a wider inner slit width, the double structure works effectively as a single-resonant structure. With even a wider gap, say 12 mm, the second resonance moves to even a higher frequency and the level of resonance is all but negligible. To target the surface-wave frequency region, it is clear that a narrow gap should be selected. The gap of 1 mm is chosen in our investigation in both BEM simulation and measurement.

Figure 7 compares the measured and predicted insertion loss. Yet again it is found that the overall agreement is good. However, the measured separation of the first and the second resonance does not seem to be as pronounced as predicted.

Figures 8 and 9 show the images of the sound field generated by the interaction of the acoustic source and the double-resonant structure. The calculation was done by the BEM and the configuration of the source and roughness elements is the same as the one used to calculate the black-lined IL in Figure 5. Figure 8 illustrate the response near the fundamental resonance; Figures 9, near the second resonance. The filled white circle at $x = 90$ cm indicates the receiver location for the black curve in Figure 5. Therefore, it will be instructive to examine Figures 8 and 9 together with Figure 5. The part (a) of Figures 8 and 9 is at the frequency where the most negative insertion loss was predicted, while the most positive insertion loss is observed at the part (b). Near the first resonance, we can see that the energy is first stored in the inner structures in Figure 8(a). Near the second resonance, the energy is stored between the inner and outer structures. Eventually, the stored energies are discharged as shown in the parts (b).

7. Conclusions

We have investigated the interaction between the roughness elements and the ground during sound propagation. Rectangular elements were placed periodically on an acoustically-hard smooth surface and were studied by both measurements and BEM predictions. First, complete rectangles – without hollow space – were studied. While it is mainly beneficial in the higher frequencies, it was shown that the acoustic performance can be affected adversely by the generation of an unwanted surface wave at low frequency. As a potential means of mitigating the surface wave effects, we have investigated propagation over resonant rectangular elements with slit openings connected to the interior hollow space. We demonstrated that the additional structural modification worked as a resonator to reduce some of the surface wave energy. To investigate tuning the resonator mechanism further, we explored a nested configuration of resonant roughness elements. Our results suggest that such single and multiple resonant structures could be designed to alter the response of the frequency range prone to the surface wave while maintaining the performance for the higher frequencies. The results reported here obtained with laboratory scale configurations can be used as the basis for designing larger scale systems for reducing outdoor noise.

Acknowledgement

The work has been funded by the Engineering and Physical Sciences Research Council (EP/K03720X/1) in the United Kingdom.

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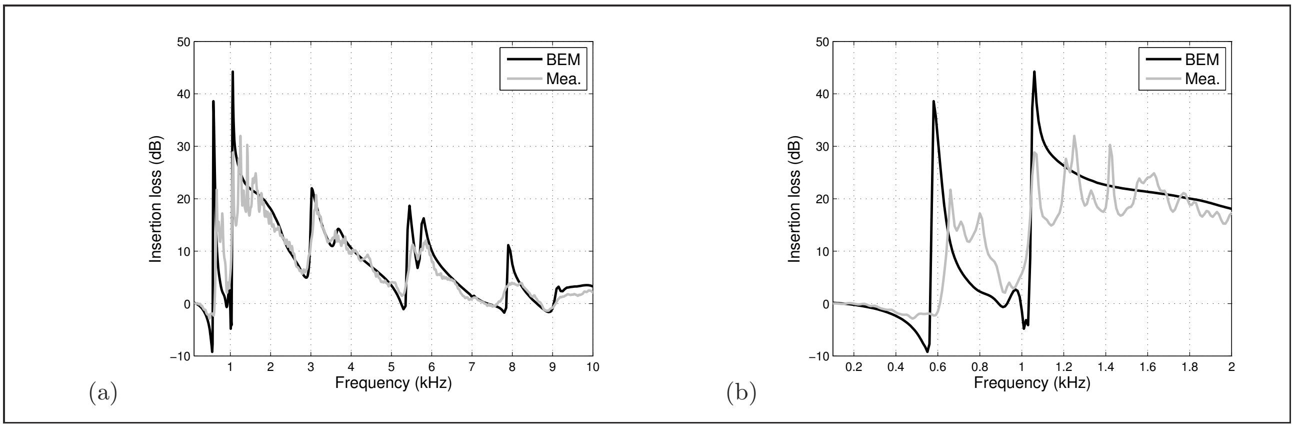

Figure 7. The comparison of the insertion loss measured (in grey) and predicted (in black) for 6 double-resonant roughness elements periodically placed on an acoustically-hard board. (a) frequency range up to 10 kHz. (b) frequency range up to 2 kHz. The outer slit gap is 6 mm; the inner, 1 mm.

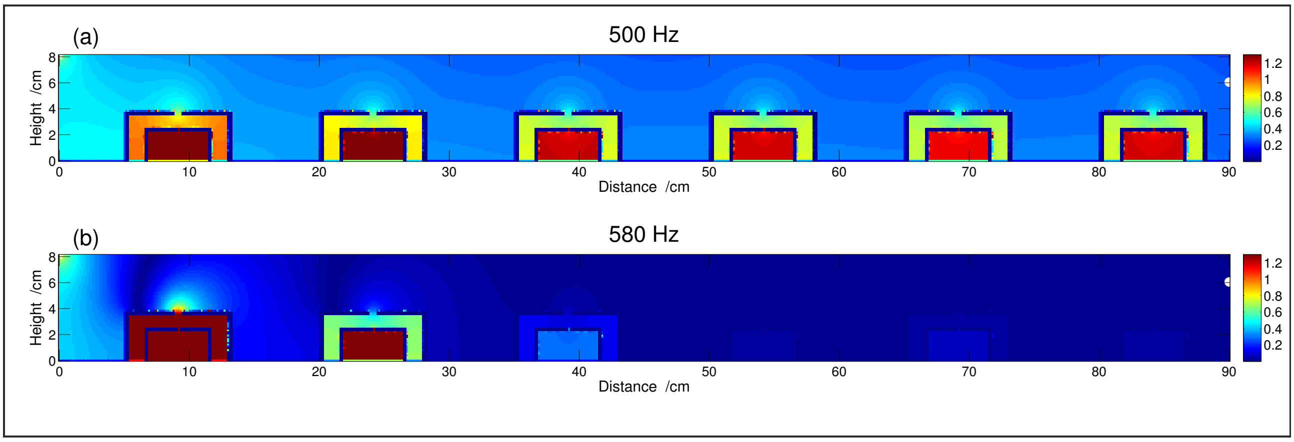

Figure 8. The sound-field image near the first resonance of the double-resonant structure. (a), 500 Hz; (b), 580 Hz. The vertical colour bar indicates the pressure magnitude in a linear scale.

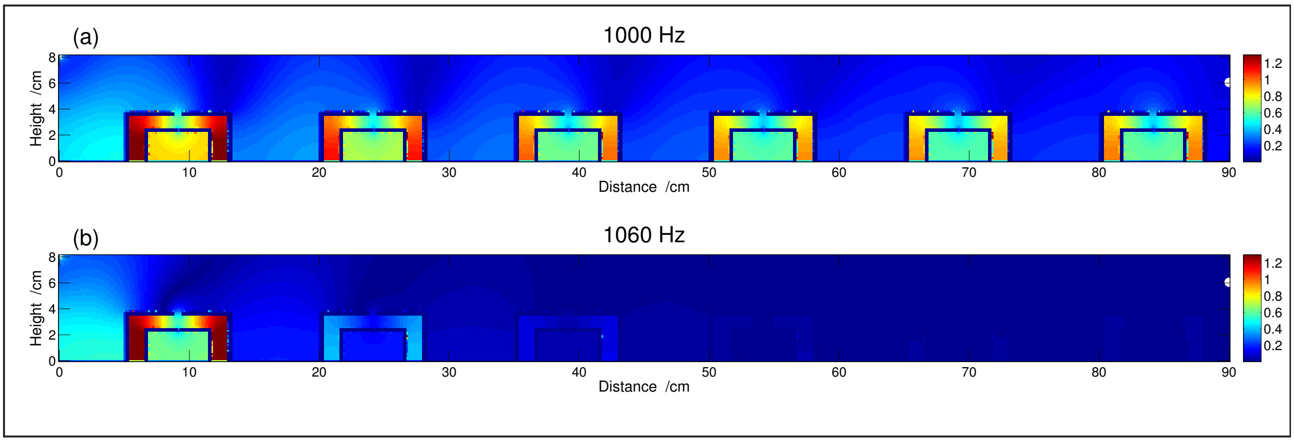

Figure 9. The sound-field image near the second resonance of the double-resonant structure. (a), 1000 Hz; (b), 1060 Hz. The vertical colour bar indicates the pressure magnitude in a linear scale.

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